PERFORMANCE ENHANCEMENT AND HEALTH MONITORING OF A MEDIUM CALIBER GUN SYSTEM USING OPTICAL FIBER BRAGG GRATING SENSORS

C. LaVigna[1], J. Bowlus[1], H. Kwatny[1], S. Chen[2], H. Zhang[2], and S. Cytron[3]

[1] *Techno-Sciences, Inc., Lanham, MD 20706.*
[2] *University Of Maryland, College Park, MD 20742.*
[3] *U.S. Army TACOM-ARDEC, Picatinny Arsenal, NJ 07806-500.*

In this paper we present a novel Fiber Bragg Grating based system to provide real time monitoring of Round Exit Velocity (REV). REV can be used for automatic fuse setting in air burst munitions and as an indication of gun system performance. The REV data provided by this system can also be used to improve aiming accuracy, and to monitor barrel wear and corrosion. In this research, a prototype REV measurement system was designed, fabricated and tested on the 25 mm M242 Bushmaster cannon. Live fire tests were conducted in single shot and burst modes with various service rounds. The results of these test showed that measured REV was accurate to within 2-3% of a reference muzzle velocity radar reference system. The results also showed that REV could be accurately measured for each round in a burst at the standard M242 burst firing rates of 100 and 200 rounds per minute. The sensor system adds negligible mass to the weapon system and it is rugged and reliable.

INTRODUCTION

The purpose of the research was to develop a system to measure round exit velocity from measurements taken while the round is still in-bore through the use of surface mounted fiber optic strain sensors. The capability to monitor in the field, in real-time, the Round Exit Velocity (REV) for medium (and large) caliber cannons would be useful for improving gun system performance, for determining barrel health, and for enabling automatic fuse programming (setting) for air burst rounds.

Important measures of gun system performance include round impact accuracy and dispersion. One of the significant factors affecting the impact accuracy on target of a given round for a modern cannon is the accuracy of the azimuth and elevation coordinates computed by the fire control system. The computation of these coordinates is typically accomplished by means of solution of a set of external ballistic equations in which the REV of the projectile is a critical input. Currently, in most fielded gun systems (some field artillery systems are the exception), REV is not directly measured. Instead, it is estimated based on nominal ammunition requirement specifications. These specifications typically specify the REV mean and standard deviation requirements for qualifying rounds fired from a standard barrel at a nominal temperature. However, in the field, many factors such as ammunition temperature, barrel temperature, and barrel wear, to name a few, can affect REV. High ammunition temperature can affect the propellant burn rate resulting in a 5-10% increase in pressure and REV. Elevated barrel temperatures can affect the interior ballistics and cause bore expansion leading to blowby of propellant gases resulting in variations in REV on the order of 5%. Finally, barrel wear can cause

substantial REV reduction and increase in dispersion. Wear can lower REV by as much as 10-20% [1].

Since the accuracy of the ballistic solution for a given round depends in part on the accuracy of the REV estimate for that round, and since it is not possible to measure the REV for a given round prior to its firing, it is critical that the REV estimate be based on the best REV statistical data available for the current gun system and ammunition conditions. This means that a system that continuously measures REV should be able to provide a better estimate of the current REV statistics than the nominal qualification data and therefore a better REV estimate from which to compute the external ballistic solution.

In addition to improving the accuracy of the round impact by increasing the accuracy of the fire control ballistic solution, real-time REV monitoring can provide an indirect indication of barrel health and wear. Trends in the REV mean and standard deviation can be analyzed online, in real-time, and compared to acceptable values to determine the remaining useful life of the barrel. This differs from typical current useful life methods, which rely on tallying the number of rounds fired from a given barrel to determine when to change out a barrel.

Finally, on-line real-time REV monitoring can be employed in a real time automatic fuse programming system for air burst munitions on automatic medium caliber canons, such as the 25 mm M242 gun system. In this type of a system, the REV sub system would be integrated with the gun fire control system and an inductive based fuse setting system that would communicate time to destruct information to a timer-based fused munition shortly after it left the muzzle. A system such as this could enable automatic programming of fused rounds for each and every round in a burst.

In view of these potential benefits, the purpose of the research was to develop a system to measure the exit velocity of a round from measurements taken while it is still in-bore through the use of surface mounted fiber optic strain sensors. The research approach included designing, analyzing, fabricating and testing a fiber optic based strain sensor system for measurement of REV in medium caliber gun barrels. This system, called the Optical Fiber Round Velocity (OFREV) measurement system is based on the following operating principles. In typical gun systems, immediately after ignition, the propellant gases generate very high levels of pressure (>50 ksi for the M242 system) and start to accelerate the projectile down the bore of the gun barrel. As the projectile moves, the gas pressure behind it generates a moving hoop strain wave, i.e., the pressure causes a measurable increase in the diameter of the barrel and this disturbance moves with the projectile. As the projectile nears the muzzle of the barrel, the acceleration slows and a nearly constant velocity is reached. This velocity can be estimated from the hoop strain wave by measuring the elapsed time for the strain wave to pass between two barrel-surface mounted (located near the muzzle) strain gages of known separation distance. The system essentially works as a speed trap, timing the hoop strain wave and computing the velocity by dividing the strain gage spacing by the measured elapsed time to obtain the average velocity of the projectile in the bore between the sensors. Since the projectile experiences a small additional acceleration for the short distance between the strain sensor closest to the muzzle and the unvented portion of the muzzle brake, a correction factor based on empirical live-fire test results is added to the measured velocity to arrive at the REV.

Current Techniques for Measurement of REV

There are a number of techniques currently employed by the ballistic community to measure REV in field and laboratory environments. In the field, muzzle velocity radars are

employed on some field artillery systems to measure REV of the outgoing round. The M94 Muzzle Velocity Radar (MVR) system, currently fielded by the U.S. Marines, employs a flat phased array antenna typically mounted onto the non-recoiling structure of a howitzer gun system. This system directly measures the velocity of the outgoing projectile via Doppler shift. For laboratory environments, yaw screens, inductive timing rings (also used in the field on the Oerlikon system), bore pressure transducers and strain gages are often employed for measurement of REV. Yaw screens and inductive rings are similar in application in that they are used to measure the passage of a projectile through two inductive coils. Typically, the coils are mounted a short distance away from the muzzle and measure REV by timing the passage of the projectile between two screens (or rings). Knowing the distance between the screens or rings and the elapsed time of travel between them, one can compute REV. For the bore pressure transducers method, two transducers are inserted into drilled and tapped holes in the barrel and are employed to detect the onset of the high pressure propellant gas wavefront as it moves down the barrel. Typically, the transducers are mounted to the barrel near the muzzle with a nominal spacing. REV is computed similarly to the yaw screen method. Another common method for measurement of REV in laboratories is based on metal foil strain gages. In this method two strain gages are attached to the surface of the gun barrel and are employed to detect the hoop strain pulse moving with high-pressure propellant gas wavefront that accelerates the projectile. Again, the REV is computed in the same method as the previous techniques.

Analysis of REV Measurement Systems for a Field Weapon Application

The previously mentioned REV measurement techniques for application on a fielded weapon system have several inherent disadvantages. The MVR is expensive ($25K replacement cost for M94 system), bulky, complex, and actively emits radar pulses. It also has a major operational drawback in that REV is measured when the projectile is in flight which is too late for integration to the inductive fuse setting system for setting of the fuse for that particular round.

The mounting and placement locations of yaw screens and inductive rings make their use difficult for application on a fielded gun system. Since the screens or rings need to be located outboard of the muzzle, a structure attached to the gun which holds them out into the projectile path would be required. In this location, the screens or coils would be subjected to the shock, vibration, temperature, and pressures generated by the muzzle blast. In order to withstand these considerable effects, the structure to hold the coils would need to be substantial and therefore heavy. The Oerlikon system mentioned in a previous section uses such coils in its design. The addition of significant mass at the end of the gun barrel adversely affects the gun barrel flexure dynamics leading to an increase in flexure induced aiming errors and limits the performance of the gun stabilization system.

The use of pressure transducers is also not well suited for this application. Barrel mounted pressure transducers require drilling holes from the outer surface directly into the barrel bore which presents barrel reliability and safety problems for use in the field on a combat weapon system.

Finally, foil strain gages are not well suited for this application. The use of electrical-resistance strain gages for ballistic research dates as far back as the early 1940's [2]. However, while they are useful for some types of ballistic research such as triggering for high-speed cameras and indirect measurement of in-bore pressures, they have significant drawbacks in this application, such as; slow data capture rates of measurement instrumentation, non-automated measurement techniques and sensor error due to electromagnetic interference (EMI). However,

the use of fiber optic strain sensors for REV measurement enables the application of this well tested concept without any of the drawbacks of foil sensors noted above.

Advantages of Fiber Optic Based Sensors System for REV Measurement

Optical fiber based sensor systems provide the following advantages important to the ballistics community. Firstly, because optical fibers are compact (5~10 μm core surrounded by a cladding of 125μm, which is only slightly thicker than a human hair). Secondly, optical fibers are mechanically robust. The mechanical strength of the optical fiber has been measured to be 5~7Gpa, which is about 7 to 10 times that of carbon steel. The use of optical fibers has been reported in applications spanning wide temperature ranges from cryogenic (-270°C) up to nearly 1000°C [3]. Examples of the use of high strength optical fiber in harsh operating conditions include pay-out fiber in TOW anti-tank missiles [4] and fiber temperature and pressure sensor inside downwells of oil fields. [5] Additionally, optical fibers are light and flexible which enables the fiber to be attached or embedded to most structures without affecting the functionality of the host. Finally, optical signals are immune to electromagnetic interference inherent in explosive environments. This property enables optical fiber-based sensors to avoid the extensive measures normally required to shield the sensors, lead wires and processing instrumentation, which often leads to a bulky and heavy system.

OFREV SYSTEM DESIGN

Internal Ballistic Phenomenon

Various dynamic and thermodynamic interactions take place among the gun barrel, propellant, projectile and external environment during an internal ballistic event. After ignition, the rapidly burning propellant creates a very high pressure inside the barrel bore behind the projectile [6]. This pressure accelerates the projectile and induces various strain phenomena in the walls of the gun barrel. One of the phenomena produced is a moving dilation in the hoop strain at the rear of the projectile that moves with the projectile as it travels from the breach to the muzzle. The proposed REV measurement system measures the velocity of this hoop strain dilation phenomenon as a means for measurement of the projectile velocity

In order to evaluate and optimize the design of the REV measurement system it is necessary to understand the motion of the projectile in the bore and the strain produced in the barrel during the firing process. These data can be obtained from live-fire tests or from internal ballistic model predictions. For this research, barrel surface strain and temperature data was obtained from a report describing live-fire tests of the M242 conducted at the Armament Technology Facility (ATF) 300 m Range at Picatinny Arsenal, NJ [7]. The strain and temperature data in this report were useful in determining the expected levels of strain and temperature during firing which are important parameters for the overall system design. Also of significance for the design is the velocity profile of the projectile in-bore. A simplified model of the internal ballistic dynamics and in-bore velocities was constructed using the data that was available.

Optical System Design and Principle of Operation

The fiber optic REV measurement system has the primary function to measure the elapsed time for the hoop strain wave to pass each of two barrel-surface mounted strain sensors. As mentioned previously, in this system optical Fiber Bragg Grating (FBG) sensors are employed as the strain sensing elements and an instrumentation system composed of fiber optic and electric components to convert the signals produced by the sensors into useable voltages for post processing (The operational principles of FBG's are described later in this paper.). For the M242 cannon the OFREV system design requirements included a maximum projectile velocity of 1400 m/s, a velocity measurement resolution of < 1% of maximum projectile velocity (i.e., 14 m/s), to withstand shock and vibration commensurate with live fire of a limited number of single rounds and a small number of bursts, and to withstand temperatures only moderately higher than ambient.

In addition to these requirements, the expected levels of strain and strain rates generated during live fire are important for optical system design. Based on the results of live fire testing reported by [8], the maximum strain levels at the expected sensors locations for the M242 gun system are estimated to be in the range 600-1000 $\mu\varepsilon$ and the strain rates as high as 500 $\mu\varepsilon/\mu s$. Consequently, the strain resolution requirement for the system in order to meet the 1% velocity measurement resolution listed above was determined to be 100 $\mu\varepsilon$.

In the design process several system configurations were evaluated to arrive at a feasible design, which is shown schematically in Fig. 1. As can be seen in the figure, the design consists of two FBG's fabricated into a single fiber, an FBG-based notch filter, a broadband source, a coupler, a photo detector amplifier and a PC with A/D card.

The main objective of the design process was to produce a system of minimal complexity and cost that met the requirements described above. In order to achieve this, the design possesses two significant features: multiplexing of the FBG's and a demodulation scheme using an FBG-based notch filter. Multiplexing the FBG's into a single fiber results in a single channel system in which the FBG's are interrogated independently thereby reducing the need for two channels of sensor signal demodulation optics and electronics. Employing the FBG-based notch filter results in a very simple configuration in which the sharp rising edge of the hoop strain wave can be detected at a sharp step in light intensity output (this will be seen later in the results of the prototype laboratory testing).

Also of major consideration in the design optimization process were the repeatability and complexity of fabrication of the FBG-based notch filter, an optical component that filters the reflected signal from the fiber strain sensors. Several different signal filtering methods and optical filter types were investigated during the design and prototype fabrication tasks. This effort resulted in a novel filter fabrication design using a standard phase mask

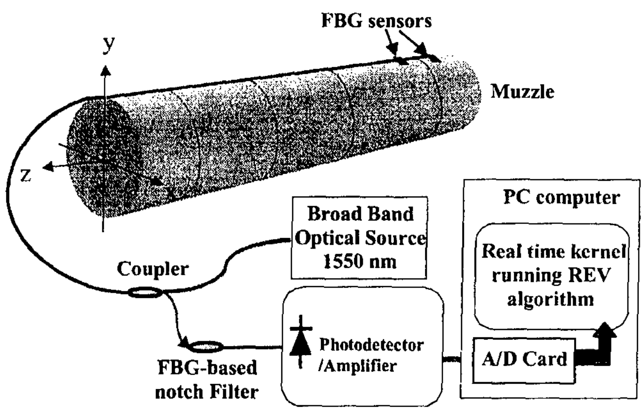

FIGURE 1: REV system configured on gun barrel.

illuminated by a 244 nm wavelength IR laser using an iris.

The remaining system design task involved development of the photo detector/amplifier, which is the instrumentation that converts the optical intensity into a useable voltage signal. In this task an amplifier was designed to interface with an MRV purchased photo detector. The amplifier was designed to have a 2 MHz bandwidth and a gain to ensure an output in the 1-5 volts range based on the expected light input to the photo detector.

The underlying principle of operation of the OFREV measurement system is quite straightforward. The sensors utilize the optical technology of the FBG, which consist of a length of optical fiber where the core of the fiber has been modified using a laser to obtain a modulation in the refractive index of the core. FBG's operate by acting as a wavelength selective filter for light passing through it and reflects a single wavelength called the Bragg wavelength, λ_B. The Bragg wavelength is related to the grating pitch, Λ, and the mean refractive index of the core, n, by

$$\lambda_B = 2\Lambda n \tag{1}$$

Both the fiber refractive index (n) and the grating pitch (Λ) vary with changes in strain (ε_{zz}) and temperature (ΔT), such that the Bragg wavelength shifts left or right in wavelength space in response to applied thermal-mechanical fields. For a Bragg grating sensor bonded to the surface of a structure, the strain and temperature are related to the change in the Bragg wavelength by

$$\frac{\Delta\lambda_B}{\lambda_B} = P_e\varepsilon_{zz} + \left[P_e(\alpha_s - \alpha_F) + \zeta\right]\Delta T \tag{2}$$

where α_s and α_f are the coefficients of thermal expansion of the structural material and fiber, respectively, and ζ is the thermal-optic coefficient, and P_e is the strain-optic coefficient [9,10]. The Bragg gratings are oriented so that they are sensitive to hoop strain, i.e., they are aligned perpendicular to the barrel axis around the outer surface of the barrel and epoxied in place. This design transfers the fast rising hoop strain from the barrel surface to the sensor. Thus it enables detection of the moving projectile as it reaches each sensor. The hoop strain dilation is detected as it passes a Bragg grating by monitoring the shift in λ_B.

By positioning the two strain sensors at a fixed separation, L, near to the muzzle and measuring the time difference, Δt, of the onset of the shift in λ_B, the REV can be estimated as

$$V_{rc} = L/\Delta t \tag{3}$$

From (3), we can calculate the minimum time resolution, $d\Delta t$, required in order for the sensing system to measure the REV to the required resolution, dV_{rc}/V_{rc} and express it as

$$d\Delta t = (L/V_{rc})(dV_{rc}/V_{rc}) \tag{4}$$

Assuming L= 0.25m, V_{rc}=1400 m/s and dV_{rc} = 7.8 m/s, we can obtain the minimum time resolution of the sensing system as 1μs, which translates to a sensor bandwidth of 1MHz. It is important to note that the REV measurement requires high speed, not high accuracy for the two Bragg grating strain sensors and the detection system, i.e., the sensor system needs to be capable

of detecting the onset of the shift in λ_B with a resolution of 1μs but does not need to accurately measure the amount of shift.

In order to meet this high-speed requirement an innovative method for detection of the shift in λ_B, was developed. The method developed consists of employing an optical notch filter with a precisely defined optical transmission spectrum in the configuration shown in Fig. 1. The spectrum of this filter is shown in Fig. 2 and is employed as follows. First, consider the case where there is no strain on either of the sensors. Light from the source passes through the coupler and a portion of it is reflected back by each of the Bragg gratings. The intensity spectra of the reflections are shown in Fig. 2. Notice that two peaks at slightly different wavelengths characterize the spectra, one for each of the sensors. The reflected light then passes through the notch filter and into the photo detector. The photo detector outputs a current that is linearly proportional to the optical *power* that it receives. Due to the shape and location in wavelength space of the notch filter, see Fig. 2, both of the intensity peaks are extinguished by the notch filter. This figure illustrates how the two peaks fit inside of the notch, which effectively blocks the transmission of optical power at these wavelengths. Therefore, no light reaches the photo detector and its output is its quiescent level. When the weapon is fired and the hoop strain dilation reaches Bragg grating sensor no. 1 it is subjected to tensile strain stretching the sensor and increasing λ_B. As λ_B increases, outside the influence of the notch filter, light is transmitted through the notch filter and into the photo detector. This effect is shown in Fig. 3. Due to the sharp slopes of the notch filter transmission spectrum and the Bragg grating reflection spectrum, even a small shifting of λ_B, produces a significantly large change in the light reaching the photo detector. Therefore, when the hoop strain dilation reaches sensor no. 1 a sharp step is seen in the photo detector output current (The laboratory test results from the Phase I prototype indicate that we will be able to detect a strain event with resolution down to 100 με or less).

As the hoop strain dilation reaches the Bragg grating sensor no. 2 it also experiences an increase in λ_B and another step increase in the light power reaching the photo detector occurs. This effect is shown in Fig. 4. The time response curve expected from the sensor system as the hoop strain dilation passes both sensors is illustrated in Fig. 5.

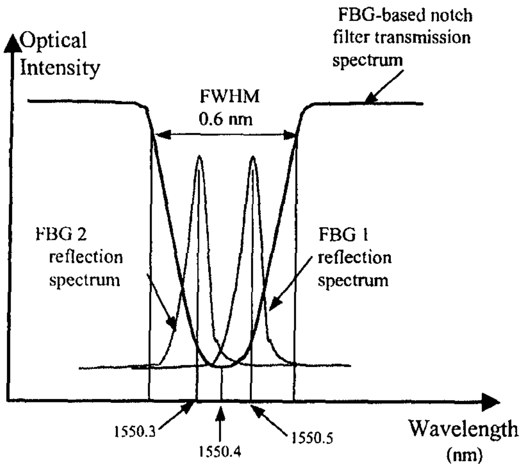

FIGURE 2: Optical intensity spectra for FBG's and FBG-based notch filter in the unstrained condition

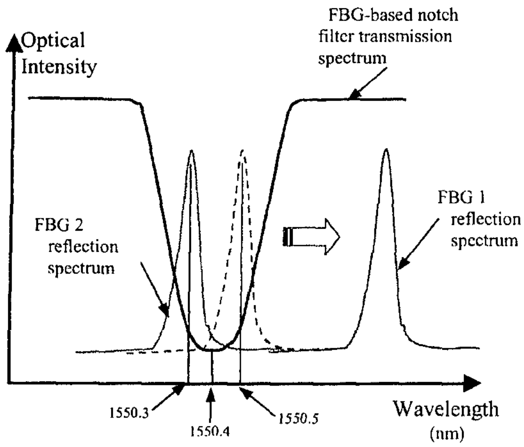

FIGURE 3: Optical intensity spectra for FBG's and FBG-based notched filter when FBG 1 is strained.

Prototype System Fabrication

In order to evaluate the feasibility of the proposed system design a prototype system was fabricated. The FBG's and FBG-based notch filter were manufactured at the fiber optics laboratory at the Smart Materials and System Research Center (SMSRC), University of Maryland. Bragg gratings were fabricated by exposing the fiber to a periodic intensity profile produced by coherent interference with Bragg wavelength of 1550.9 and 1550.7, respectively. The FBG-based notch filter was fabricated using single mode fiber and a unique fabrication process using a reduce diameter (2 mm) UV laser for fringe writing with a standard phase mask. This was achieved by passing the laser light through an iris before the phase mask interface. The overall effect of this procedure was to increase the full width half maximum (FWHM) length (from 0.1 nm to 0.9 nm) of the wavelength spectrum to band stop, under non-strain conditions.

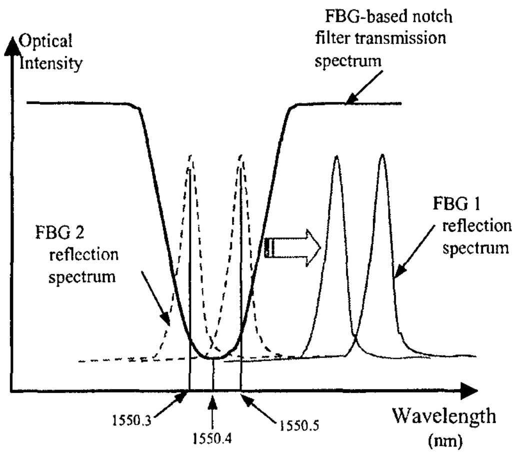

FIGURE 4: Optical intensity spectra for FBG's and FBG-based notch filter when FBG 1 and FBG 2 are strained.

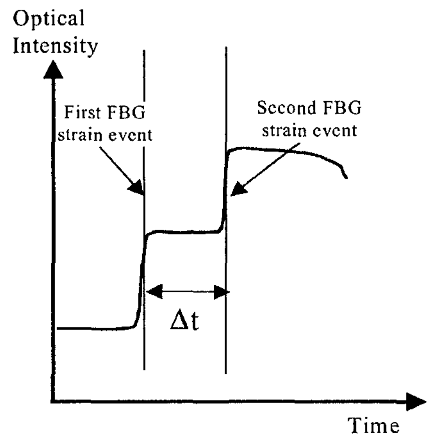

FIGURE 5: Expected optical output intensity time history for successive straining of FBG 1 and FBG 2

Arrangement of FBG Strain Sensors on M242 Gun Barrel

The results of the sensor placement analysis indicated that to achieve the velocity measurement accuracy and resolution targets, the sensor should be mounted as close to the muzzle as possible and spaced at least 10 cm apart. Using the results of this analysis, the sensors on barrel no. 1 were located on the barrel with the sensor closest to the muzzle being located approximately 4.5 cm inboard of the muzzle and with a sensor-to-sensor spacing of 20 cm. In order to evaluate the system performance with the sensors at the minimum spacing, the sensors on barrel no. 2 were spaced 10 cm apart, with the sensor closest to the muzzle also located at approximately 4.5 cm in board of the muzzle. For both barrels, the sensors were orientated perpendicular to the axis of the gun barrel to measure hoop strain.

LIVE-FIRE TESTING OF OFREV MEASUREMENT SYSTEM

Testing Description and Procedures

Live fire tests were conducted on two OFREV equipped M242 25-mm gun barrels. Barrel no. 1 was equipped with both an OFREV system and a foil strain gage system. The foil strain

gages were mounted in close proximity to the OFREV strain sensors to enable system debugging and performance evaluations. The spacing of the two OFREV strain sensors (and the foil strain gages as well) was 20 cm with the strain senor mounted closest to the muzzle being located within approximately 4.5 cm of the muzzle. Barrel no. 2 was equipped with an OFREV sensor system with 10 cm spacing of the OFREV strain sensors and also, like barrel no. 1, with the strain senor mounted closest to the muzzle being located within approximately 4.5 cm of the muzzle. The outputs from each system were connected simultaneously to a high-speed (1 MHz sample rate) digital oscilloscope and a National Instruments PC-based DAQ card installed in a Pentium PC host. The oscilloscope was connected to a laptop for data storage. The LabView system enabled direct streaming of the captured data to the PC hard drive.

In order to evaluate the accuracy of the OFREV measurements a Weibel Scientific W-680I Doppler Analyzer was used as a reference. This system tracks the projectile as it leaves the muzzle and computes the muzzle velocity based on its trajectory. The system is limited to measurement of the muzzle velocity of the first round in a multiple round burst

Testing Description and Results

Several test were conducted for each of the barrels using different ammunition types and under single and burst shot modes. Table 1 provides important characteristics of the tests conducted, indicating the test no., barrel no., round type, and firing mode (single shot or burst) for each of the tests. During each of the tests listed, data was collected from the OFREV, strain gages (for Barrel no.1 only), and the Weibel MVR system. For the tests involving burst mode, it was only possible to measure the muzzle velocity of the first round in the burst using the MVR.

TABLE 1: Test characteristics.

Test No.	*Barrel No.*	*Round Type*	*Firing Mode - Single/Burst (rate)*
Test1	1	M793	Single
Test2	1	M793	Single
Test3	1	M793	Single
Test4	1	M793	Single
Test5	1	M793	Single
Test6	1	M793	Single
Test7	1	M793	Single
Test8	1	M793	Single
Test9	1	M793	Single
Test10	1	M793	Single
Test11	1	M793	Burst – 2 Rnds (100 rpm)
Test12	1	M791	Single
Test13	1	M910	Single
Test14	1	M793	Burst – 5 Rnds (200 rpm)
Test15	2	M910	Single
Test16	2	M910	Single
Test17	2	M910	Burst – 3 Rnds (100 rpm)
Test18	2	M793	Single
Test19	2	M793	Burst – 20 Rnds (200 rpm)

The data from each of the tests were analyzed to compute the estimated round exit velocity (or muzzle velocity). This was done by examining the OFREV output for each of the tests and graphically estimating the width of the OFREV output signal pulse.

Single Shot Firing Mode Tests

Fig. 6 illustrates a typical time response curve generated by the OFREV system during the firing of a single round. Table 2 shows the estimated REV, reference REV, and error percentage for each of the single shot tests conducted. OFREV data were not available for Test1, Test7, and Test16 due to data collection triggering problems. The average error in the estimated REV for the tests shown in the table is 2.2 %. The errors for Test2 and Test3 were high due to optical fiber sensor temperature calibration related issues. After these issues were resolved, the average error dropped to 1.6 %. This error compares well with an OFREV system design accuracy target of 1 %.

Burst Shot Mode Firing Tests

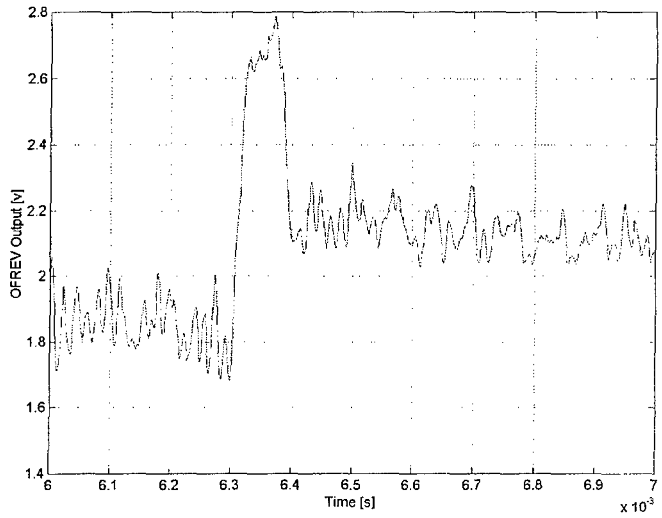

FIGURE 6: Typical OFREV system output response for a single shot.

The burst mode data was analyzed according to the same procedure as the single shot mode data. This analysis was performed for as many shots in the burst as possible. Due to errors introduced when the barrel temperature increased during firing, only the first several shots in a burst could be analyzed. Table 3 shows the round type, estimated REV, reference REV, and error percentage for each of the shots in a burst in which there was valid data. Note that the Weibel MVR was limited to measurement of the REV of the first round in a burst. Consequently, the error of the OFREV measurement was only computed for the first round. Inspection of the data in Table 3 for the rounds after the first for each burst indicates an increase in the error if we assume that the reference velocity for each of the rounds is close to that of the first round in each burst. This is most likely due to heating of the barrel and is an expected effect since the system design did not include temperature compensation features. The effects due to the increase in temperature can be seen in Fig. 7, which shows a typical OFREV time response curve for a burst mode test (Test14). Note that the average level increases as the rounds are fired. This rise is related to an increase in the temperature of the barrel, which induces thermal strain in the system.

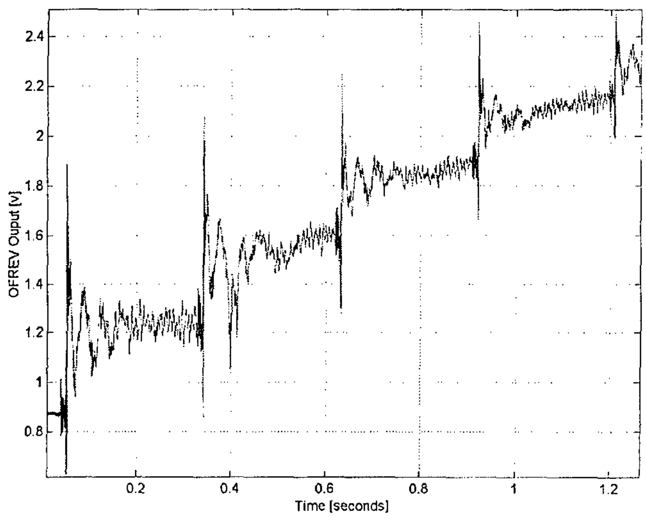

FIGURE 7: Typical OFREV output for a burst (Test 14)

Also, the data from the burst mode tests indicates that the system response is sufficiently fast with adequate resolution to enable measurement of REV for each round in a burst at firing rates of 100 and 200 rounds per minute. Automation of the elapsed time data extraction for the OFREV will enable real time REV measurement under burst mode for air burst munition applications.

The results of the testing also indicate that the system was sensitive to changes in temperature as the barrel is heated during firing, especially for multiple round bursts. This effect can be minimized using barrel attachment techniques that thermally isolate the optical sensor.

CONCLUSIONS

A prototype system was designed, fabricated and tested under live fire indoor test range conditions on an M242 25 mm cannon. The OFREV system performed quite well in the live fire tests. The results of the 19 firing tests of over 40 rounds showed that the system could measure the REV to within 2-3% of the reference MVR system for the three different types of rounds. It is likely that an improvement in the system accuracy could be achieved by taking into account the additional unmeasured acceleration from where the velocity measurement was made (the OFREV system essentially computes the average projectile velocity between the strain sensors) to outboard of the muzzle, since the projectile is still experiencing a small acceleration in this region.

In addition to achieving good accuracy, the OFREV system demonstrated an output waveform very suitable for automated feature extraction. The shape of the system output signal pulse generated by a firing event was sharp with a high signal-to-noise ratio, which will make it very conducive to a high-speed automatic elapsed time extraction algorithm.

Finally, the system held up quite well under the shock and thermal loads generated during the firing of over 40 rounds, including the high velocity M910 and M791 rounds. The fiber sensors did not break nor was there any evidence of failure in the adhesive used to bond the sensor to the barrel.

TABLE 2: Results of OFREV round exit velocity estimates for single round tests

Test No.	*Round Type*	*OFREV estimated REV (m/s)*	*Weibel reference REV (m/s)*	*Error (%)†*
Test1	M793	N/A	1102.3±1.2	
Test2	M793	1025.6	1093.2±1.4	-6.2
Test3	M793	1043.4	1090.5±1.3	-4.3
Test4	M793	1085.8	1093.8±1.1	-0.7
Test5	M793	1073.0	1090.2±1.6	-1.6
Test6	M793	1082.3	1090.5±1.5	-0.8
Test7	M793	N/A	1085.9±1.9	
Test8	M793	1076.4	1095.4±1.4	-1.7
Test9	M793	1077.6	1090.3±1.8	-1.2
Test10	M793	1078.2	1097.2±1.2	-1.7
Test12	M791	1303.8	1338.4±1.2	-2.6
Test13	M910	1496.2	1498.2±1.3	-0.1
Test15	M910	1439.1	1506.1±2.4	-4.4
Test16	N/A	N/A	1501.1±2.0	
Test18	M793	1078.0	1089.8±1.4	-1.1

† Error computed based on nominal Weibel reference REV value.

TABLE 3: Results of OFREV round exit velocity estimates for multiple round burst tests

Test No. (round no. in burst)	*Round Type*	*OFREV estimated REV (m/s)*	*Weibel reference REV (m/s)*	*Error (%)†*
Test11 (1)	M793	1082.3	1090.7±1.7	-0.8
Test11 (2)	M793	1033.3	N/A	
Test14 (1)	M793	1060.8	1088.4±1.7	-2.5
Test14 (2)	M793	1005.5	N/A	
Test14 (3)	M793	1027.3	N/A	
Test14 (4)	M793	1032.4	N/A	
Test14 (5)	M793	1026.6	N/A	
Test17 (1)	M910	1425.8	1513.3±2.1	-5.8
Test17 (2)	M910	1469.6	N/A	
Test17 (3)	M910	*	N/A	
Test19 (1)	M793	1106.8	1094.9±1.7	-1.1
Test19 (2)	M793	1158.3	N/A	
Test19 (3)	M793	1091.4	N/A	
Test19 (4-20)	M793	*	N/A	

† Error computed based on nominal Weibel reference REV value.
* Data not available due to elevated barrel temperatures.
Note: Reference values only available for first round in burst due to Weibel MVR limitation.

ACKNOWLEDGEMENTS

This work was supported by a U.S. Army SBIR Phase I grant under contract number: DAAE30-00-C-1019. Special thanks for support and guidance to the staff of TACOM-ARDEC at Picatinny Arsenal, NJ.

REFERENCES

1. S. Cytron, personal communications, March 30, 2001.
2. Flynn, Paul D., "Application of Strain Gages to Ballistics Problems," Frankford Arsenal Report no. FA-TA-74008, August 1974
3. Morse TF 1999, He Y and Luo F, "An optical fiber sensor for the measurement of elevated temperatures", Proceeding of 13th Optical fiber sensor conference, Kyongju, Korea, SPIE proc. Vol 3746, pp.54-57.
4. Culshaw, B. 1988, Dankin, J., *Optical Fiber Sensor: Systems and Applications*, Vols. 1 and 2, Artech House, Norwood, MA.
5. Kersey AD 1999, "Optical fiber sensors for downwell monitoring applications in the oil and gas industry", Proceeding of 13th Optical fiber sensor conference, Kyongju, Korea, SPIE proc. Vol 3746, pp.326-331.
6. Tzeng, Jerome T, and Hopkins, David A, "Dynamics Response of Composite Gun Tubes Subjected to a Moving Internal Pressure," U.S. Army Research Laboratory Report no. AR-TR-889, October 1995.
7. Aesoph, Michael D, Czarnek, R, and Miller, C, "Advanced Gun Barrel Technology Initiative: Instrumentation and Testing Report for a Modified Unlined M242 Barrel," National Center for Excellence in Metalworking Technology, Contract N00140-92-BC49, Test Report, September 30, 1996.
8. James, Stephen W, Fuller, Stephen R., Crompton, C., and Tatam, Ralph P., "Transient Strain Monitoring on a Gun Barrel Using Optical Fibre Bragg Grating Sensors," SPIE Conference on Laser Interferometry IX: Applications, San Diego, CA, July 1998.
9. Sirkis, J.S. 1993, "A Unified Approach to Phase-Strain-Temperature Models for Smart Structure Interferometric Optical Fiber Sensors: Part I-Development," *Optical Engineering*, 32 (4), pp. 752-761.
10. Meltz, G. R. 1989, Morey, W. W., and Glen, W. H., "Formation of Bragg Gratings in Optical Fibers by a Transverse Holographic Method," *Opt. Letts.*, 14, pp. 823-825.